Issues Related to Large Flight Hardware Acoustic Qualification Testing

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ABSTRACT

The characteristics of acoustical testing volumes generated by reverberant chambers or a circle of loudspeakers with and without large flight hardware within the testing volume are significantly different. The parameters attributing to these differences are normally not accounted for through analysis or acoustic tests prior to the qualification testing without the test hardware present. In most cases the control microphones are kept at least 2-ft away from hardware surfaces, chamber walls, and speaker surfaces to minimize the impact of the hardware in controlling the sound field. However, the acoustic absorption and radiation of sound by hardware surfaces may significantly alter the sound pressure field controlled within the chamber/speaker volume to a given specification. These parameters often result in an acoustic field that may provide under/over testing scenarios for flight hardware. In this paper the acoustic absorption by hardware surfaces will be discussed in some detail. A simple model is provided to account for some of the observations made from Mars Science Laboratory spacecraft that recently underwent acoustic qualification tests in a reverberant chamber.

KEY WORDS: Acoustics, vibro-acoustics, direct acoustics, reverberant chambers, loud speakers, acoustic absorption and radiations

INTRODUCTION

Most spacecraft and many of their components, such as reflectors and solar panels, are flight qualified by acoustic testing either using reverberant chambers or loudspeaker arrangements. The acoustic field controlled in most chambers provide near diffuse field, except at low frequencies where the fundamental modes between the chamber walls provide acoustic standing waves. The diffusivity of a chamber can be assessed by considering resonance peaks that are closer than the bandwidth associated with any one peak. The Schroeder cut-off frequency, which defines the lowest frequency where the chamber acoustic field may be considered diffuse, is given by[1],

$$f_{sch} = \left(\frac{C^3}{9.21}\right)^{1/2} \left(\frac{T_{60}}{V}\right)^{1/2}, \tag{1}$$

where C is the sound speed, T_{60} is the reverberation time in the chamber, and V is the chamber volume in m^3. For the JPL reverberant chamber with a volume of approximately 290 m^3, the sound speed at room temperature of 340 m/sec, and the reverberation time close to 1 second, the f_{sch} is estimated to be approximately 120 Hz. The cut-off frequency increases when a large test article occupies a significant portion of the chamber's volume. For the acoustic qualification of flight hardware one of the requirements is to generate sound pressure levels within the testing volume that are diffuse, at least above several tens of Hz, whether the test is performed using reverberant chambers or loudspeakers arrangements. The modal density for reverberant chambers below f_{sch} is small and causes spatial variability that departs from an acceptable diffuse acoustic field. It has been recently demonstrated that acoustic standing waves within the chamber below the cut-off frequency could couple with the test articles structural modes and result in significant increase in the structural responses as discussed in a paper by Kolaini et al[2].

The volume of the test article with respect to the reverberant chamber volume or the loudspeakers testing volume is another important parameter that impacts the controlled sound pressure fields. In this paper we provide a qualitative discussion on the acoustic absorption of the hardware and its impact on controlling the sound pressure levels (SPLs) in the chamber.

EXPERIMENTAL RESULTS

In this paper data from Mars Science Laboratory (MSL) spacecraft acoustic test performed at the JPL reverberant chamber is discussed. The size of this spacecraft with respect to the chamber volume as depicted in Figure 1 provides a perfect opportunity to discuss its impact on the controlled SPLs. The MSL spacecraft underwent acoustic qualification test in stowed configuration. It consisted of several dozen components, some of which were engineering and mass models. The spacecraft was placed on a GSE transporter and was rolled into the chamber once it was in a test-ready configuration. The total mass of the spacecraft was approximately 3,700 kg and the total mass of the transporter was approximately 3,640 kg. The GSE transporter was approximately 1.26 meters above the ground. This helped minimize the impact of the reflected sound waves from the floor on the spacecraft critical components. The acoustic field within the chamber was controlled using the average sound pressure levels from eight microphones positioned away from the spacecraft, chamber walls, and tight spaces between the chamber and the spacecraft (Figure 1 shows some of the control microphones, which are suspended from ceiling). In addition to eight control microphones 16 response microphones, scattered around the spacecraft closer to most acoustically driven surfaces of the spacecraft, were also employed (Figure 1b shows one of the response microphones closer to the spacecraft). These monitor microphones were used to aid in the understanding of the acoustic field around the spacecraft in real time. The spacecraft components were instrumented with several dozen triaxial accelerometers during system assembly to monitor the dynamics of components at their interfaces in real time, and strain gages to monitor stresses on the critical locations of the solar panels. The structural response results are not discussed in this paper.

Before the full level spacecraft acoustic qualification test was performed, the empty chamber was calibrated to the required specification. Figures 2a and 2b show the SPLs without and with the spacecraft plotted in 1/3 octave band at full level, respectively. The sound pressure variation between the eight control microphones, the average levels, the upper and lower tolerances, and the qualification levels are shown in these figures. The modulator used for controlling the sound field within the chamber was a WAS3000 manufactured by Wyle Corporation[3]. The modulator's upper operational frequency as recommended by the manufacturer was 680 Hz. The higher frequency (i.e. greater than 680 Hz) noise, in general, is generated by the combination of the jet noise induced by injecting gas into the chamber and the passage of acoustic waves that become nonlinear as they propagate through the horn. At very high acoustic intensities chambers in the horn throat that normally produce a sine wave degenerate into a saw tooth as the temperature gradient generates differences in the propagation velocity. The saw tooth wave has a very steep wave front which creates harmonic excitation, with part of the low frequency energy of the random noise transferred to high frequencies by this process[3]. This helps fill in the noise levels in the mid to high frequencies. The high frequency noise is augmented by the noise generated by the gas injecting into the chamber. It has been demonstrated that the JPL chamber can achieve reasonable high frequency sound pressures with a gas pressure of 18 psi when the modulator is controlled up to 1000 Hz. The spacecraft acoustic data discussed in this report, however, was taken by setting the upper frequency for the modulator at 10,000 Hz. This was done by the staff without considering the potential degradation in efficiency of the modulator and its impact on sound generation and levels it produces in the chamber.

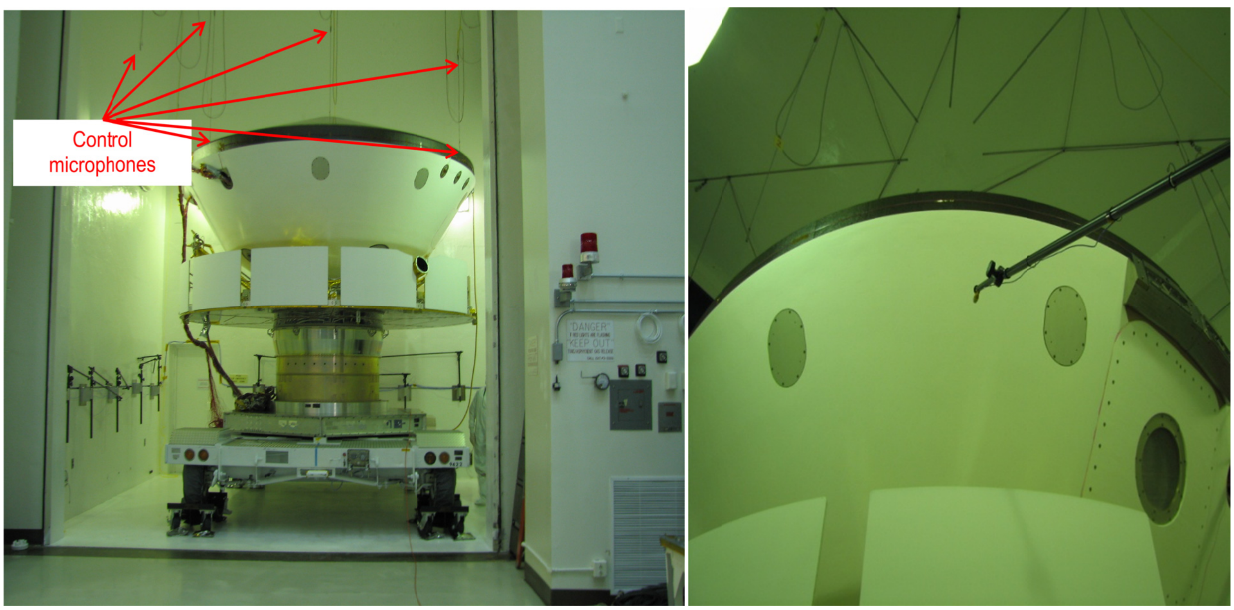


Figure 1: The MSL spacecraft acoustic qualification test performed at JPL's reverberant chamber. The spacecraft is being rolled in to the chamber in ready-to-test condition. The control microphones for this test were suspended from the chamber's ceiling several feet from the spacecraft. A monitor microphone close to the aero shell is shown in (b).

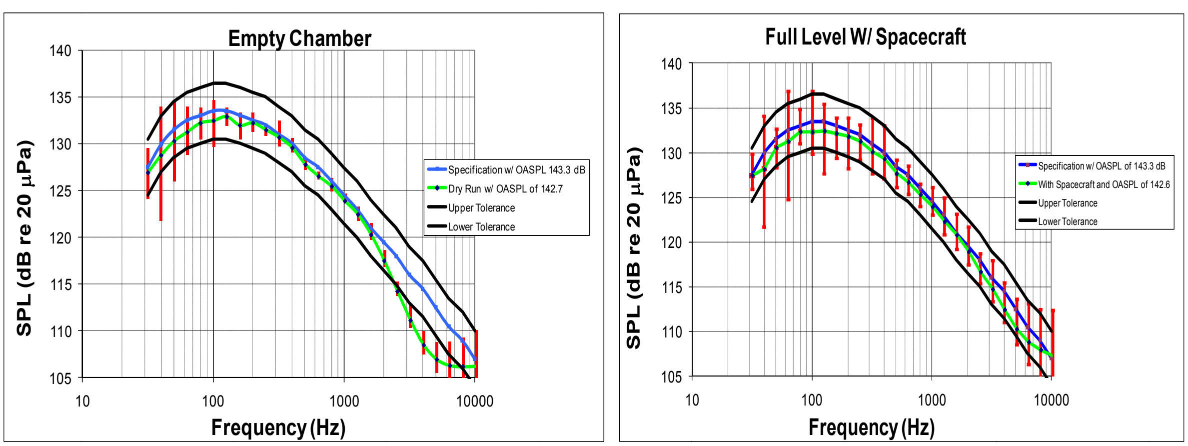
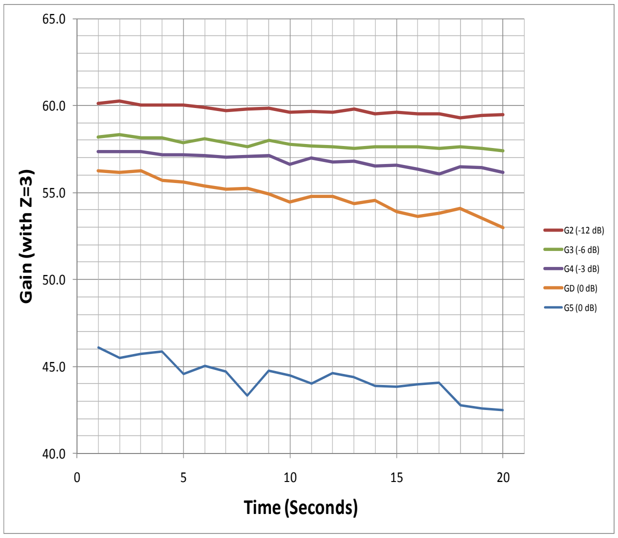


Figure 2: The average control sound pressure levels in the chamber a) without the spacecraft, and b) with the spacecraft. The average of eight microphones (green curve) is compared with the required levels (blue curve); the tolerance levels (black curves) are also shown in these figures. The deviation from the mean pressure levels (red lines) is provided to gauge the spatial variation in the chamber with and without the spacecraft.

As is the case with any enclosure, there are acoustic standing waves (typically up to a dozen or so modes) that create significant spatial variability in the chamber. This usually happens below the Schroeder cut-off frequency, which is close to 120 Hz for this chamber. As Figures 2a and 2b show, the standing waves may provide more than 15 dB variations in the SPLs within the chamber[2]. The test article in the chamber, especially a large one such as the MSL spacecraft, changes the standing wave patterns and shifts the spatial variation upward in the frequency domain. The impact of test article on the chamber acoustic modes can be significant and is the subject of future investigation. There are a few noticeable differences in the SPLs when comparing them for cases with and without the spacecraft. First, the sound field does indeed change across all frequency bands with a large test article in the chamber. The spatial variation in the SPLs at lower frequencies (up to 400 Hz) are more pronounced as discussed earlier since the volume inside the chamber is decreased and the acoustic standing waves are broken down to smaller wavelengths, therefore, affecting the f_{sch} estimated using Eq. (1). Figure 2b also shows the volume occupied by the spacecraft impacts higher frequencies. In fact, the spatial variation of the SPLs is increased and the levels above ~2000 Hz are closer to the average required SPLs than the empty chamber data. Second, the acoustic reflections and deflections had probably occurred due to the spacecraft surfaces that may have contributed to the SPL differences depicted in Figures 2a and 2b. Finally, the acoustic absorption by the spacecraft, in particular the heat shield and aero shell, impacts the SPLs within the chamber. The absorption of sound by the spacecraft is discussed below in some detail.

The energy supplied to the chamber through the horn using WAS3000 modulator can be assessed using the data gathered from the MSL spacecraft acoustic test. Several cases are considered for this purpose. The gain factor in the control system used to estimate the energy delivered by the modulator to the chamber is obtained using test runs with -12 dB (G2), -6 dB (G3), -3 dB (G4), 0 dB (G5) with the spacecraft, and the empty chamber at full level (GD). For all these runs the control system's upper frequency was set at 10,000 Hz. The power supplied to the modulator was estimated using rms voltage output of the control system, the current supplied to the modulator, and the gain factor computed over a 1-second interval. To demonstrate the linearity of the system, the Gain (G) is calculated and plotted in Figure 3a using $I_{mp}I_{out}/V_{in}$, where V_{in} is the measured voltage supplied to the WAS3000, and I_{out} is the output current, and I_{mp} is the measured impedance of the WAS3000 modulator based on 3Ω at 1 kHz. Figure 3a also shows the gain factor computed for lower levels with the spacecraft and the full level runs with and without the spacecraft (G5 and GD). The estimated gain factors for the lower level runs with the spacecraft and with the empty chamber run at full level are within the typical ranges used for chamber operation at JPL. However, the gain factor estimated at the full level with the spacecraft is significantly lower than the same without the spacecraft in the chamber. The main reason for this is the voltage required to operate the modulator exceeded the maximum rms voltage of 0.5 set in the control system prior to the test. This resulted in the voltage data being clipped, therefore, impacting the estimated gain factor as shown in Figure 3a. The modulator energy required to generate the sound pressure levels in the chamber is estimated using $V_{in}I_{out}G$. The estimated energy for full level runs with and without the spacecraft is plotted in Figure 3b. The energy estimated with the spacecraft in the chamber shown in this Figure is obtained using the gain factor computed from the clipped data (red curve) and the gain factor obtained from the empty chamber run (blue curve). Considering the fact that the energy estimated with the spacecraft in the chamber had data clipping issues, plots in Figure 3b qualitatively indicate the modulator energy required for the controller to sustain the required SPLs in the chamber has significantly increased in the presence of the spacecraft. It is possible that the true energy of the modulator, without the data clipping issue, would have probably been higher than the one shown in Figure 3b. One of the major contributing factors for the increased modulator energy is believed to be the acoustic absorption by spacecraft large surfaces that forced the WAS3000 modulator to work harder to accommodate the required SPLs within the chamber.



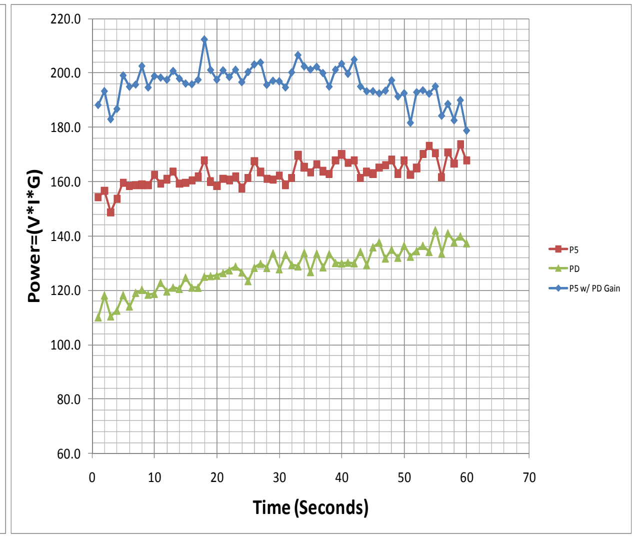


Figure 3: a) The controller gain factor estimated with spacecraft (-12 dB, -6 dB, -3 dB, and 0 dB) and without (0 dB, GD), and b) the estimated modulator power delivered to the chamber with and without the spacecraft at full level. The estimated power using the gain factor based on the clipped data from the full acoustic level test with the spacecraft (red curve) and with the gain factor obtained with empty chamber (blue curve) are shown in (b).

ACOUSTIC ABSORPTION

To qualitatively assess the acoustic energy absorbed by the spacecraft surfaces, in particular the heat shield and aero shell; we begin with the acoustic power delivered to the chamber, which is balanced by the modulator's energy through the combination of horn and chamber efficiency, η,

$$W_{in} = W_{out} = \eta W_{modulator}. \tag{2}$$

Equation (2) is applicable to the chamber with and without test articles. The horn efficiency in the presence of the test article is assumed to change slightly and is, therefore, ignored. The average sound pressure in the chamber is given by[4-5]

$$\langle P^2 \rangle = \eta \left| \frac{4\varrho C}{(\sum A_i\alpha_i + \sum A_i\tau_i + 4mV)} \right| W_{modulator}, \tag{3}$$

where α_i is the absorption coefficient, τ_i is the sound transmission coefficient, ρ is the density of the nitrogen gas, A_i the surface areas absorbing the acoustic energy, V is the volume, and m is the total mass of gas. The first term in the denominator is the acoustic energy absorbed by the chamber walls and the spacecraft surfaces, the second term is the acoustic transmission, and the third is the absorption in the gas within the chamber, which is insignificant for the problem discussed in this paper. Let's assume for simplicity that the acoustic transmission is also small, which is corroborated by relatively benign structural responses measured at the components interfaces inside the MSL heat shield and aero shell. With these assumptions, Eq. (3) becomes,

$$\frac{\langle P^2\rangle_{w/}}{\langle P^2\rangle_{w/o}} \approx \frac{\left[\eta\left|\frac{4\varrho C}{(\sum A_i\alpha_i)}\right|W_{modulator}\right]_{w/}}{\left[\eta\left|\frac{4\varrho C}{(\sum A_i\alpha_i)}\right|W_{modulator}\right]_{w/o}}. \tag{4}$$

The chamber coupling efficiency, η, is the sum of the modal overlap and chamber walls efficiency. Again the chamber walls and modal overlap efficiencies are assumed to remain the same with and without the test article. This assumption is valid for the horn efficiency; however, the modal overlap efficiency in the presence of the test article will be different. This effect is ignored in this paper and will be included in future studies. With these assumptions, Eq. (4) is simplified to,

$$\frac{\langle P^2\rangle_{w/}}{\langle P^2\rangle_{w/o}} \approx \frac{[W_{modulator}]_{w/}}{\left[1+\frac{(\sum A_i\alpha_i)_{spacecraft}}{(\sum A_i\alpha_i)_{chamber\ walls}}\right][W_{modulator}]_{w/o}}. \tag{5}$$

Equation (5) simply indicates that the increase in the absorption of acoustic energy by the spacecraft surfaces forces the modulator to work harder to sustain the required pressure spectral levels in the chamber (i.e. $\frac{\langle \boldsymbol{P^2}\rangle_{\boldsymbol{w/}}}{\langle \boldsymbol{P^2}\rangle_{\boldsymbol{w/o}}}$ to be near unity). The estimated increase in the average modulator energy is more than 50% in the presence of the spacecraft in the chamber as shown in Figure 3b. The increase in the modulator energy is significant and could impact the modulator's operation as well as the structural components of the spacecraft in the chamber.

Figure 4 shows the acoustic pressure squared ratio of one of the control microphones to the monitor microphone closer to the spacecraft surfaces as a function of 1/3rd octave frequency. Above a few hundred Hz, the decrease in the sound pressure levels in the presence of the spacecraft is believed to be due to the absorption of the acoustic energy by the spacecraft, in particular the heat shield and aero shell structures. The absorption of the energy would be higher if the additional energy spent by the modulator in sustaining the required SPL in the chamber is included as discussed before. This would roughly add another factor of 2 (3 dB) to the data shown in Figure 4. Not all the changes shown in Figure 4 are attributed to the absorption of the acoustic energy by the spacecraft's heat shield and aero shell. There are potential acoustic radiation, scattering, and bending of waves that may also account for some of the differences shown in Figure 4, especially from a few tens of Hz to a few hundreds of Hz.

When large flight hardware is acoustic tested in a reverberant and/or loudspeakers arrangement, the impact of the hardware on the acoustic field generated, in general, is not assessed by the test engineers. The general belief amongst the aerospace engineers is that the changes in the sound field within the testing volume is minimal and do not raise any hardware qualification concerns. However, the acoustic data obtained from the MSL spacecraft qualification test, a relatively large article with respect to the chamber volume, provides enough information to highlight the importance of this effect. To further examine the impact of the acoustic absorption by the spacecraft surfaces the sound pressure data obtained by using the monitor microphones close to the spacecraft are shown in Figures 5-7. In Figure 5 the SPLs from the monitor microphone are compared with a nearby control microphone. The reduction in the SPLs above a couple of 100 Hz is shown in this figure. Similar reduction is clearly demonstrated in Figures 6 and 7 measured in different locations in the chamber closer to the spacecraft and compared with nearby control microphones. These figures clearly demonstrate that the presence of the spacecraft changed the sound field in a significant way. This behavior provides a few important points that impact the flight hardware qualification and should be assessed in any flight hardware qualification test. First, the test article with large absorbent surfaces soak up considerable amount of energy as depicted in Figure 3 and discussed earlier. Second, the distribution of the acoustic energy within the chamber is changed significantly (see Figure 2b). Third, because of the absorption of the acoustic energy by the test article the controller system has to force the modulator to work harder in an effort to sustain the required sound pressure levels in the chamber. This has implication on flight hardware such as the MSL spacecraft that the input energy had to be increased by as much as 50% of the energy required for the empty chamber to sustain the required acoustic environment. During launch the external sound pressure levels of a vehicle do not change from the nominal maximum expected environment. The acoustic levels measured inside the fairing with payloads of different surface absorbing characteristics will have different internal acoustic environments for the same nominal external acoustic levels. In the interpretation of the internal acoustic levels measured during the flight using a limited number of sensors the absorption of the acoustic energy by payloads should be taken into account.

Based on the aforementioned discussions it is reasonable to assume that some of the MSL spacecraft components were inadvertently exposed to much higher acoustic levels. This conclusion was arrived at considering the differences in the modulator's energy with and without the spacecraft. This issue may have drawbacks on some sensitive components as far as their structural health is considered. For the MSL spacecraft the acoustic induced structural vibration of the components interfaces inside the heat shield and aero shell were measured to be a lot lower partly due to the absorption of the acoustic energy. On the other hand, the acoustically responsive solar arrays and radiator panels, where the acoustic waves were directly impingent on them, may provide under- and or over-test conditions in certain frequency bands because of the absorption of the acoustic energy and acoustic radiation by them.

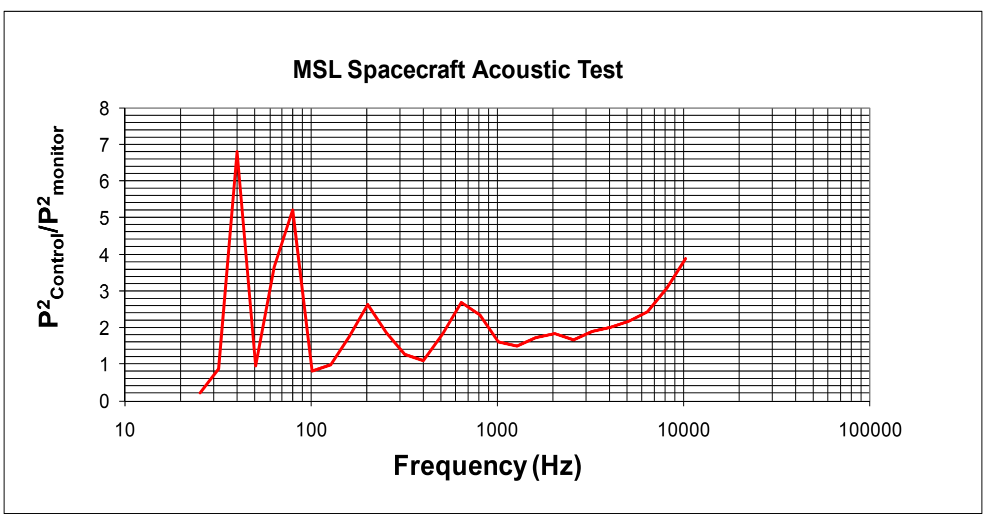


Figure 4: The sound pressure squared ratio of control microphone and monitor microphone close to the spacecraft surface. The control microphone used in this plot is the closest to the monitor microphone.

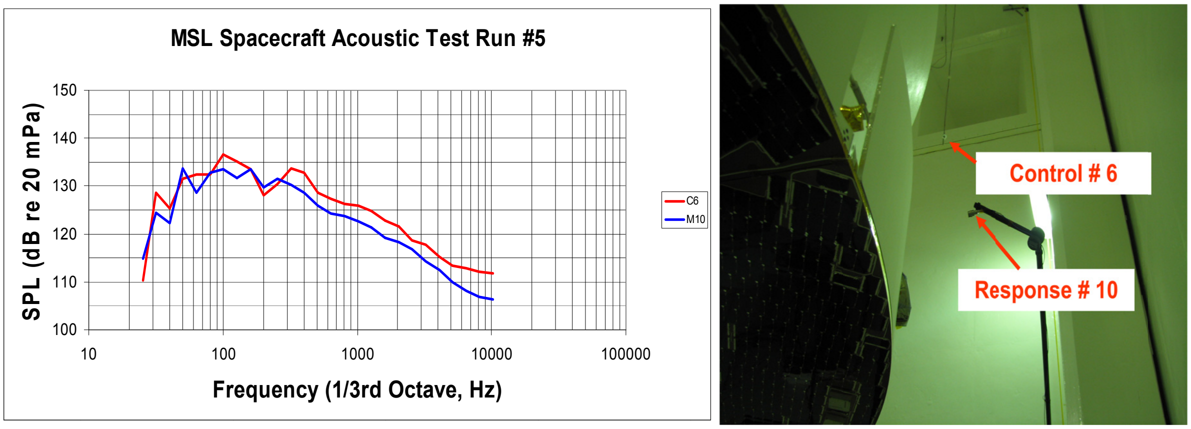


Figure 5: The SPLs measured by a control microphone (C6) closer to the monitor microphone (M10). The reduction in the SPLs above ~100 Hz is clearly shown in this figure.

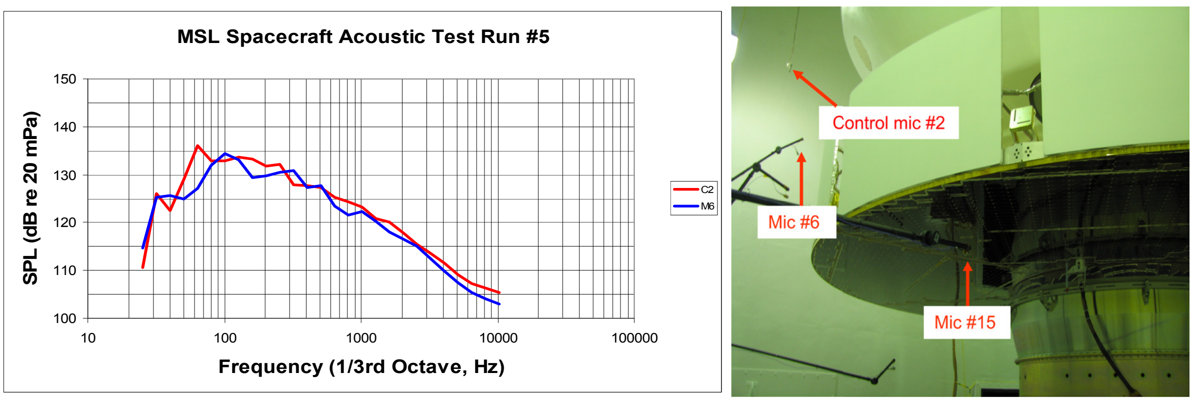


Figure 6: The SPLs measured by a control microphone (C2) closer to the monitor microphone (M6). The reduction in the SPLs above 100 is clearly shown in this figure. In some frequency bands there is evidence of amplification that most likely is due to the radiation by the radiator panels.

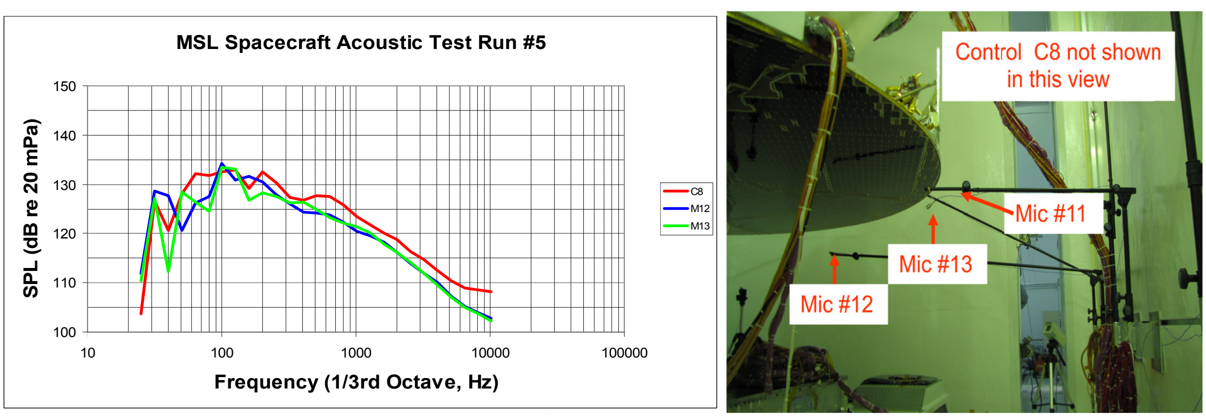


Figure 7: The SPLs measured by a control microphone (C8) closer to the monitor microphones (M12 and M13). The reduction in the SPLs above 100 is clearly shown in this figure. In some frequency bands there is evidence of amplification that most likely is due to the radiation by the radiator panels.

SUMMARY AND CONCLUSIONS

Flight hardware is qualified for launch acoustics using reverberant chambers and loudspeakers. In general, the impact of the size and volume of the hardware with respect to the volume of the chambers is not assessed by most test engineers. To highlight this effect, we discussed sound pressure data obtained from the MSL spacecraft acoustic qualification test. The spacecraft is relatively large compared to the size of the JPL chamber with its heat shield and aero shell having high acoustic absorbent surfaces. For the controller system to sustain the acoustic levels in the chamber with the spacecraft to the required levels, the modulator energy was significantly increased. A simple argument was provided on the absorption of the acoustic energy by spacecraft surfaces to be the prime candidate causing the modulator energy to increase. This provided a few points that may be important for flight qualification testing. First, the spacecraft was acoustic tested to much higher input energy. The modulator's energy had to increase by more than 50% to sustain the require SPLs. Second, the microphones closer to the spacecraft indicated much lower pressure levels at certain frequency bands than those away from it. The sound radiation by the test article also impacts the controlled acoustic field, especially at lower frequencies. The radiation and absorption of the acoustic energy impact the controlled acoustic field in a significant way. Using the control microphones closer to the test article surfaces to obtain the desired acoustic levels are not recommended. The benign vibration levels measured at components' interfaces inside the heat shield and aero shell are believed to be partly due to the absorption of energy by these structures. However, those components such as solar arrays and radiator panels with direct acoustic impingment may have received over testing condition at certain frequency bands. Finally, the controller parameters, control strategy for generating the required SPLs for relatively large hardware, and location of control microphones must be examined before selecting a testing facility. The information provided in this paper are preliminary and further examination of the effect of the acoustic absorption and radiation are needed and are planned in the future.

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REFERENCES

1. A.D. Pierce, Acoustics: An Introduction to its Physical Principles and Applications, Acoustical Society of America, 1989.
2. Ali R. Kolaini, Michael R. O'Connell, and Wan B. Tsoi, "Acoustically Induced Vibration of Structures: Reverberant vs. Direct Acoustic Testing," 25th ATS, October 2009.
3. Airstream Modulator Model WAS 3000 Operational Manual, Wyle Laboratories, 7800 Governors Dr., W. Huntsville, AL 35807, April 1978.
4. Determination of sound power levels of noise sources using sound pressure – Precision method for reverberation rooms, ISO 3741: 1999, ANSI S12.51-2002, Nationally Adopted International Standard (Acoustical Society of America, New York, 2002).
5. Philip M. Morse and K. Uno Ingard, Theoretical Acoustics, McGraw-Hill, 1968.

BIOGRAPHIES

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Mr. Dennis Kern has worked in vibration, acoustic and shock prediction and testing for aerospace structures and components for 39 years. Since 1978, he has supervised the dynamics environments activities at the Jet Propulsion Laboratory, supporting all JPL flight projects and managing numerous technology development programs. Mr. Kern has played a major role in the development of several NASA and industry standards and handbooks and has organized the annual NASA/USAF/Industry Spacecraft and Launch Vehicle Dynamics Environments Workshops since 1988.